Assessing Climate Change Effects on Mountain Ecosystems Using Integrated Models: A Case Study

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1. Introduction

Mountain systems are characterized by strong environmental gradients, rugged topography and extreme spatial heterogeneity in ecosystem structure and composition. Consequently, most mountainous areas have relatively high rates of endemism and biodiversity, and function as species refugia in many areas of the world. Mountains have long been recognized as critical entities in regional climatic and hydrological dynamics but their importance as terrestrial carbon stores has only been recently underscored (Schimel et al. 2002; this volume). Mountain ecosystems, therefore, are globally important as well as unusually complex. These ecosystems challenge our ability to understand their dynamics and predict their response to climatic variability and global-scale environmental change.

To meet this challenge, mountain scientists increasingly are modeling the vast array of relationships that comprise ecosystem dynamics. Dynamic modeling can examine the interactions between land management strategies and climatic change to develop appropriate responses to future human demands on mountain systems. Modeling provides spatially and temporally explicit, quantified results that can be

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validated in the field, thus providing feedback to our understanding of ecosystem dynamics. Modeling results, particularly maps and other visual tools, also give a concrete dimension to our understanding of the scale and magnitude of potential future changes. Modeling alerts scientists and land managers to apparently counter-intuitive outcomes of ecosystem responses to climate change or management decisions. For instance, in an early modeling exercise for northwest Montana, USA, Running and Nemani (1991) found that streamflow in a warmer future climate decreased by 30% in the Swan Range even when precipitation was increased by 10% in a particular climate change scenario. This unexpected response was due to enhanced forest growth, and increased evapotranspiration, resulting from the earlier snowmelt and extended growing season.

There is a rich legacy of models that address climate and weather, hydrology, forest growth (e.g. gap dynamics and succession), forest fires (e.g. fuel loading) and land cover change (cf. Bugmann et al., this volume). Much less common, however, are attempts to fully integrate models from various disciplines to create a robust system that adequately addresses the entire range of ecosystem dynamics. In addition, fine-resolution modeling of entire mountain ranges (i.e. regional ecosystem scale) is not as common as global or continental scale modeling or watershed/catchment scale modeling. However, this is the scale that is germane to policy decisions such as in the western US and Canada, i.e. in those areas that contain most of the mountainous terrain of North America. This paper describes our efforts to implement an integrated regional modeling approach while characterizing potential future responses of a mountain ecosystem to climate change. Our study area was Glacier National Park in northwestern Montana, USA. Glacier Park is a 4082 km^2 mountain wilderness that straddles the continental divide and contains over 150 summits of up to 3150 m elevation in the Lewis and Livingston mountain ranges.

2. Model background

The integrated modeling program for Glacier Park was built on previous efforts and developed into two related models, the Regional Hydro-Ecological Simulation System (RHESSys) and FIRE-BGC (Fire BioGeoChemical).

2.1 Modeling ecosystem patterns and processes

RHESSys is an evolving group of regional hydroecological models that are designed to simulate the coupled cycles of water, carbon, and nitrogen. This modeling system has been modified to provide appropriate input/output data to each sub-model and collectively address ecosystem patterns and processes in mountain regions (Running et al. 1989; Band et al. 1993). Several spatial databases are required to initialize and run RHESSys, including digital elevation models (i.e. topographic relief) and soil properties. Remotely sensed data from satellite platforms provide another spatial database on the distribution and density of vegetation on the ground, required for calculating biophysical processes. Data sources include AVHRR (Advanced

Very High Resolution Radiometer) at 1 km^2 resolution and Landsat TM (Thematic Mapper) at 30 m resolution. From these data, vegetation indices are calculated, such as Leaf Area Index (LAI), that estimate the potential photosynthesis. Combined with climatic and other environmental data, these indices are used by models to estimate the productivity of vegetation (for details see White et al. 1998). In RHESSys, vegetation is not represented as community types but as broad plant functional types, which differ in their carbon storage capacity and ecophysiological properties, such as photosynthesis and respiration. These vegetation estimates are overlaid on a digital elevation model (DEM) that represents the park's topography in three dimensions at up to 10 m resolution, and a topographic soils index (TSI) that combines existing soil data and estimates of water movement through the terrain (Band et al. 1993). The result is a static model-based description of the current state of Glacier Park.

From this starting point, the simulation is made dynamic by supplying daily meteorological variables to the model. These are generated for different aspects and elevations of the mountain landscape by taking daily data from a meteorological station in the valley bottom and using MT-CLIM (a Mountain Climate simulator) (Hungerford et al. 1989) to estimate maximum and minimum temperatures, relative humidity, short-wave radiation and other climate variables. Based on information about slope, aspect, elevation, soil moisture holding capacity, daily estimated weather and estimated initial vegetation biomass, spatially-explicit calculations of daily tree growth can be made. At the heart of RHESSys is the biogeochemical model FOREST-BGC (Running and Gower 1991) that estimates ecosystem attributes, such as gross primary productivity, at daily time-steps. The simulation results of FOREST-BGC are mapped across the mountain landscape on an annual basis. FOREST-BGC interacts with a hydrological routing model to estimate daily soil moisture and stream discharge of water that is not used in evapotranspiration. Thus, the results from this integrated modeling system for a specific watershed include net primary productivity as well as net ecosystem carbon exchange, aboveground and soil carbon pools, carbon-to-nitrogen ratios and daily to annual hydrologic discharge.

2.2 Modeling ecosystem structure and fire disturbance

FIRE-BGC is a closely related integrated model that emphasizes the structural components of the mountain forest ecosystem and includes forest fires as a key disturbance factor. This model simulates forests in a similar way to how they are perceived by people (forest structure and composition) rather than as estimates of photosynthetic activity, which is not directly observable. The model does not yet include hydrologic routing and discharge estimates. FIRE-BGC shares FOREST-BGC as a common component with RHESSys for estimating nutrient cycling and other ecosystem processes but merges it with the forest gap model FIRESUM (Keane et al. 1996). This sub-model allows FIRE-BGC to estimate rates and trajectories of post-disturbance succession and provides important compositional and structural attributes, such as tree species dominance, stand age, and coarse woody debris. These latter attributes are critical for estimating fuel loads, which greatly affect the potential occurrence of large, stand-replacing wildfires, and for simulating fire intensity and size, using companion models such as FARSITE (Fire Area Simulator) (Finney and Ryan 1995). FIRE-BGC is a multi-scale model, working from individual trees and aggregating up through plots and tree stands to landscapes. A multi-scale approach is necessary because some ecosystem processes, such as fire and seed dispersal, occur only at the landscape level, whereas other processes, such as organic matter accumulation and tree establishment, can be modeled at the stand level. FIRE-BGC is tree-species specific and includes competitive relations between trees that alter the responses to the broad environmental drivers included in RHESSys. Thus, for a mountain ecosystem such as Glacier Park, FIRE-BGC can map mosaics of forest stands of different ages and composition, resulting from both climatic variability and forest fires, and can provide details of tree stand dynamics, such as depth of duff and litter on the forest floor. FIRE-BGC also interfaces well with other forest science research and models so that different forestry management scenarios can be examined. For example, FIRE-BGC and a smoke management model could be paired to estimate the long-term effects of different fire suppression policies on regional air quality.

2.3 Model validation

To determine whether these models provide an accurate picture of the dynamics of this mountain ecosystem, we gathered field data on key ecosystem processes to compare with the estimates from the models. Many of these field studies have been generating information for 10 years, providing a spatially-extensive dataset for other mountain research endeavors and further model validation. We focused on two watersheds for initial model development and field validation. Lake McDonald watershed is approximately 462 km^2, is located west of the continental divide, and receives predominantly maritime climatic influences. St. Mary watershed is similar in size, abuts the Lake McDonald watershed east of the continental divide, and has stronger continental climatic influences. Both watersheds are relatively pristine and undeveloped, have extensive conifer forests, receive most of their annual precipitation as snow, and contain remnant glaciers.

Results of field validation have been previously reported (Fagre et al. 1997; White et al. 1998) but are summarized below. The agreement between model results and field observations is clearly scale-dependent. For example, for RHESSys results, good agreement with field data was obtained for the distribution of snow water equivalent (Fagre et al. 1997; White et al. 1998) at hillslope and watershed scales (e.g. r^2=0.95) but less so for point or plot scales (e.g. $r^2 = 0.78$). A major constraint to fine-resolution snow estimates was the inadequacy of satellite-based LAI estimates at appropriate scales. LAI values were derived from 30 m pixels but considerable variation in forest canopy density can occur within that pixel. The forest canopy, in turn, influences the snow water equivalent because it intercepts and sublimates falling snow. Thus, the model estimates of snow distribution are limited by LAI estimates. Another issue was the variability in snow distribution, due to micro-topographic relief that was not included in the models. For watershed-scale simulations, however, the snow estimates proved sufficient. For both watersheds, hydrologic discharge simulations tracked daily discharge data closely, except for storm events where some over-prediction was noted

(White et al. 1998). At Glacier National Park, only 4 of 84 watersheds have as much as 3% of their area covered by glacial ice and 18 watersheds have only 1%. Nonetheless, in watersheds with remnant glaciers, observed discharge values during late summer were higher than model simulations, which underscored both the contributions of glacial meltwater to streamflow and the need to include this source in future models of mountain hydrology in the region. Additionally, modeled daily estimates of stream temperatures throughout the watershed closely matched daily measurements from 7 monitored streams (Fagre et al. 1997).

Carbon budget estimates for the watersheds indicated close agreement with observed values for soil CO_2 effluxes and productivity for both low and high elevation forests that cover 75% of the watersheds. For grassland sites, modeled soil CO_2 effluxes and productivity were higher than observed because of difficulties in LAI estimation for grasses. Forest stem production estimates agreed with observed values when aggregated by hillslope areas > 10 ha.

White et al. (1998) concluded that RHESSys generated reasonable estimates of ecosystem processes and attributes for these watersheds. These estimates included net primary productivity, evapotranspiration, available nitrogen and other major forest processes driving ecosystem change. Some estimates of ecosystem attributes, such as net primary productivity, were much less sensitive to scale than hydrologic discharge (White and Running 1994).

Results from FIRE-BGC simulations were also compared to field data, collected from 110 circular 0.4 ha forest plots in the Lake McDonald and St. Mary watersheds. Ecological characteristics of all plant communities were assessed by choosing plots with representative combinations of slope, aspect and elevation. An additional 98 ground-truth plots, distributed across both watersheds, were used for validation of satellite imagery classifications. A 44-year climate record was used to drive a FIRE-BGC simulation of tree growth and predicted tree ring widths. These ring widths for 44 years compared well with those taken from actual trees and suggested that FIRE-BGC was capturing annual variation in growth responses adequately (Keane et al. 1997). However, young tree growth was over-predicted while large tree growth was under-predicted for shade intolerant trees, underscoring the need to improve carbon allocation routines for a greater diversity of stand conditions.

In summary, both models were able to make reasonable estimates of most ecosystem attributes and processes for which we obtained field observations. Validating these models by comparing results to observed data provided confidence that the models were accounting for most major ecosystem processes at Glacier National Park.

3. Results of modeling future climate scenarios

After having established the models' capacities to simulate the Glacier Park mountain ecosystem and its responses to current climatic variability, we applied various climate scenarios to estimate potential future conditions of the park. This predictive, or forecasting, ability provides managers with a valuable tool for assessing a range of climate change scenarios and ecosystem responses for Glacier National Park but does not actually predict the future. Rather, RHESSys and FIRE-BGC translate possible future climate change into spatially-explicit effects on the park landscape with a reasonable degree of confidence.

3.1 Direct vegetation responses to climate change

One scenario of climate change was based on an evaluation of four general circulation models and several downscaling approaches to provide a "most likely" climate change scenario for the Glacier Park area (Ferguson 1997). This downscaling effort is especially critical for mountain environments with strong climatic gradients that are not captured by general circulation models. This scenario projects a 30% annual precipitation increase and a 0.5°C annual temperature increase by 2050. Based on this climate change, the FIRE-BGC model projected shifts in the distribution and dominance of tree species, including a reduction in subalpine fir (*Abies lasiocarpa*), as treelines rise, and a significant expansion of Engelmann spruce (*Picea engelmannii*) at the expense of lodgepole pine (*Pinus contorta var. latifolia*). Because this climate change scenario did not lead to greater fire frequency, these vegetation changes appear to be due to increased precipitation and less snowpack persistence. Using another climate change scenario, RHESSys tested the effects of an extremely variable climate but without long-term increases in temperature or precipitation. After 120 years, long-term net primary productivity of conifers in Glacier Park decreased by 4% on the western side of the continental divide and by 13% on the eastern side (White et al. 1998). The eastern side currently has a more continental climate that is drier and inherently more variable. Thus, the additional climatic variability simulated in this scenario stressed vegetation to a greater degree. According to RHESSys, broad-leaved shrubs and alpine vegetation increased by 2-7%, perhaps because periods of low snowfall increased establishment rates into areas where current snowpack prohibits establishment. Grass net primary productivity at the forest-grassland ecotone decreased because severe drought conditions became more frequent under this more variable scenario. In fact, the lower treeline (the forest-grassland ecotone) rises under this scenario due to water stress, reducing the amount of forest cover in the St. Mary watershed. These RHESSys results do not account for any increased fire frequency due to the periodically drier environment and vegetation on the eastern side. Only the plant physiological responses, such as water and nitrogen stress, are estimated. Undoubtedly, some vegetation shifts would be accelerated by altered fire frequencies, producing even greater changes in this mountain ecosystem.

Ecosystem models can also be used to elucidate changes in limiting factors that drive plant interactions and ecosystem function. For example, in both models water and nitrogen indices are calculated as part of the carbon allocation process, and these indices integrate information about water stress, nutrient availability, and the potential ratio of shoot-to-root growth. Under current conditions, growth is limited by nitrogen availability for conifer forests and shrubs, but grasses are water limited. However, under the extremely variable climate scenario, some limitations change. For instance, alpine vegetation is water-limited under the current climate but becomes nitrogen limited under the variable climate scenario. The relative nitrogen limitation for conifer forests decreases and grasses at lower treeline become much more water-limited. Partly these limitation shifts are due to resource availability as competition for resources changes but physiological requirements also change in some instances. Nitrogen sequestration increases with woody biomass accumulation. This, in turn, may decrease nitrogen cycling and therefore increase nitrogen limitation in alpine vegetation. These shifts in limitations, as simulated by the ecosystem models, can provide ecologists with more specific constraints to predict how individual species will fare under changing environmental conditions and how biodiversity patterns will change for different vegetation types. For example, as atmospheric nitrogen deposition increases in alpine environments, the nitrogen-limited alpine vegetation under the variable climate scenario will respond differently than the water-limited alpine vegetation under the current climate.

3.2 The response of fire disturbance to climate change

Wildfire is the primary disturbance process in northern Rocky Mountain forests and greatly influences carbon cycles in mountain ecosystems. Under future climate scenarios, FIRE-BGC clearly indicates that the resulting more productive forest landscapes will be exposed to more frequent and severe fires than the same landscapes experienced historically, even with the predicted increase in annual precipitation (Keane et al. 1997). Fuel loads will increase more quickly under generally wetter, warmer conditions but inherent climatic variability will still ensure the occasional drought and hot temperatures that will lead to more intense and extensive wildfires. This change in the frequency and severity of fires would nearly double smoke emissions in the future, jeopardizing the pristine air quality that the Glacier Park area currently enjoys and posing a management challenge for park managers who need to restore historic fire frequencies. Without restoring historic fire frequency, during which frequent, low-intensity fire kept fuel loads from building up, the risk of catastrophically intense fires that can consume most of the biomass is increased and could limit any vegetation growth in the affected area. Because fire frequency has been altered by humans throughout the northern Rocky Mountains for the past century, fuel loads have built up to levels that could lead to larger and more intense fires than might have been experienced in the past. Keane et al. (1997) examined the interplay of different fire management policies coupled with different climate scenarios. In the absence of fire suppression, after 250 years of simulation, fires burned over 55% and 67% of the Glacier Park landscape under a current and future climate scenario, respectively. The resulting landscapes were more productive and diverse than the landscapes that developed during the simulations without fire. These latter landscapes became marginally productive and tended to respire more of the carbon dioxide fixed by photosynthesis than did the communities in which fire played a major role. Keane et al. (1997) found that the fire-maintained early successional communities create overall landscapes that release less carbon to the atmosphere than landscapes without fire. This is true under both current and future climate scenarios and even when carbon emissions during fires are considered. There are implications of long-term fire suppression for global carbon balance if other landscapes behave similarly to those simulated in this study.

4. Modeling at larger scales

4.1 The CLIMET project

Much of the integrated modeling program described here had been focused on two watersheds in Glacier National Park of approximately 500 km^2 each. This is the scale at which many policy decisions regarding natural resource protection are made. We felt the need to test these models at larger scales of mountain national parks (approx. 5000 km^2) and mountain parks within their mountain-dominated regions (approx. 20,000 km^2) to examine scale issues. Another need was to integrate landscape fragmentation and other human disturbance into model results and to test model performance in other mountain systems. Accordingly, the CLIMET (**C**limate **L**andscape **I**nteractions – **M**ountain **E**cosystem **T**ransect) project was developed. This project investigates a transect of three distinct mountain bioregions, with large mountain national parks as core research sites, from the Pacific Coast to the Rocky Mountains. The national parks are Glacier in the northern US Rocky Mountains, North Cascades in the Cascade Mountains, and Olympic in the Olympic Mountains near the Pacific Coast. All are large, wilderness-dominated parks near the United States-Canada border. Each park encompasses mountains with similar topographic relief, numerous glaciers and expansive conifer forests; each is characterized by high winter snowfall, acts as the headwaters for its region and contains relatively intact floral and faunal assemblages.

These parks represent a transect of climatic influences, with dominant air masses providing Olympic with a maritime climate, North Cascades with a transitional climate and Glacier with a more continental climate. Olympic has the greatest landscape fragmentation outside its borders; Glacier has the least. Precipitation varies dramatically between westside and eastside locations within each park. For example, precipitation in the Olympic Mountains ranges from >600 cm/yr on Mt. Olympus to only 40 cm/yr in the northeastern rainshadow. This contrast in precipitation over relatively small distances has a profound impact on microclimate, vegetation distribution and disturbance regimes. It allows us to model and compare climatically distinct paired watersheds within each park and scale up to the bioregion and CLIMET scales.

4.2 First results

Three years of field data have been collected in the paired watersheds from each park for modeling. In addition, the DAYMET climate model (Thornton et al. 1997) was applied to the CLIMET transect. DAYMET takes existing climate data from meteorological networks, interpolates daily temperature and precipitation between existing stations, and extrapolates these parameters across topographic features and network gaps, using seasonally adjusted lapse rates. It also estimates relative humidity and radiation; both key requirements for ecosystem models. The end result is spatially-explicit climate data at 1 km^2 resolution for the past 18 years that will be a major template upon which ecosystem models are run. The DAYMET product suggests that the CLIMET transect is climatically more diverse than other areas in the US (Fig. 1), providing a good test of mountain ecosystem responses to regional climatic variation.

Temporal climate variability for CLIMET was also examined and our results suggest that multi-decadal patterns have been significant influences and should be accounted for in the future scenarios used to drive models. The Pacific Decadal Oscillation (PDO) is a broad-scale, recurring pattern of ocean-atmospheric variability (Mantua et al. 1997) that affects mountain snowpacks even on the eastern edge of the CLIMET area (Selkowitz et al. 2002). A principal components analysis of five paleoproxy reconstructions of the PDO suggests that the PDO has been a robust feature of North Pacific climate variability since 1840 and has probably been operating at least since 1600 (Gedalof et al. 2002). However, it has not been uniformly coherent and seems to have been stronger in the 20th century, based on intercorrelation between the proxies. Nonetheless, the PDO has influenced regional tree growth and other natural resources to varying degrees for a long time and the environmental effects of decadal-scale climate variability need to be taken into account in future integrated model scenarios.

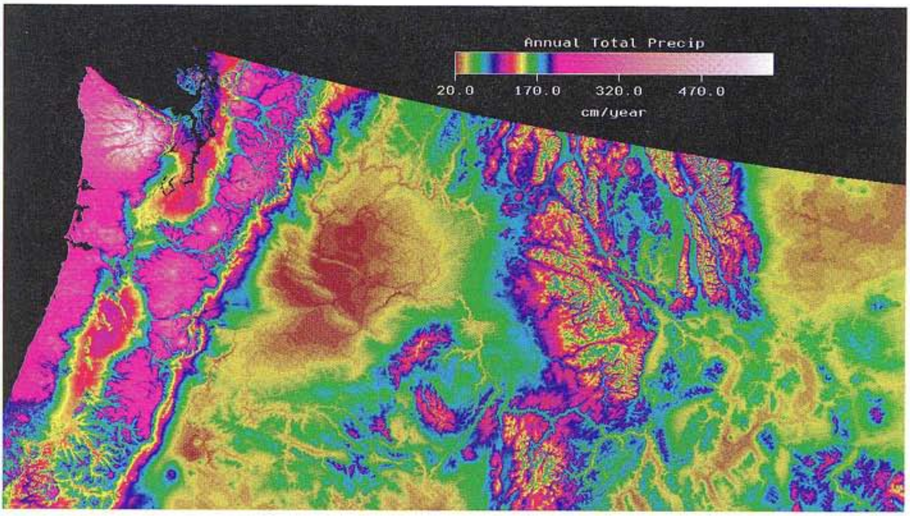

Figure 1: Distribution of annual precipitation from 1980-1997 across the Climate Landscape Interactions – Mountain Ecosystem Transect (CLIMET) program described in text. The western US contains remarkable climatic and ecologic diversity, ranging from temperate rainforests to deserts and including three major mountain systems. The upper edge of the figure corresponds to the 49°N parallel separating the US and Canada. The Olympic Peninsula, surrounded by the Pacific Ocean, is on the upper left. The Rocky Mountains of Idaho and Montana (US) are in the center right and the Great Plains are on the far right.

The first results from integrated modeling of the CLIMET transect are based on DAYMET climatic data and BIOME-BGC, a model with elements from RHESSys adapted for regional scales (Kang et al. 2002). Leaf Area Index (LAI) values from field sites in the Olympic and North Cascades mountains of CLIMET show close correspondence with potential LAI estimated by BIOME-BGC (Fig. 2). Net Primary Productivity (NPP) was estimated and mapped across this topographically complex region for current conditions (Fig. 3). The spatial distribution of NPP appears to be reasonable, based on comparisons to vegetation cover maps. NPP data from field validation sites in two of the mountain ranges indicate that, at a regional scale, the model is able to estimate a key ecosystem attribute and will prove as useful as it did at the watershed scale. Future work will focus on analyzing spatial patterns of NPP that relate to land use history, the relative role of protected areas, and responses to potential future climates.

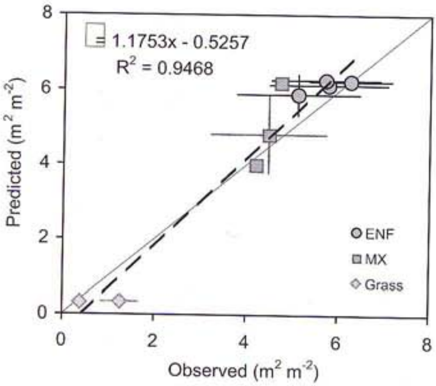

Figure 2: Relationship between field measured Leaf Area Index (LAI) and potential LAI from an integrated ecosystem model for the CLIMET transect. LAI is a proxy measure of vegetation productivity. Field sites were four watersheds in the Olympic and North Cascades mountains of western Washington State located in the northwestern US. ENF = evergreen needle forest, MX= mixed deciduous forest, Grass = several types of grasslands (from Kang et al. 2002).

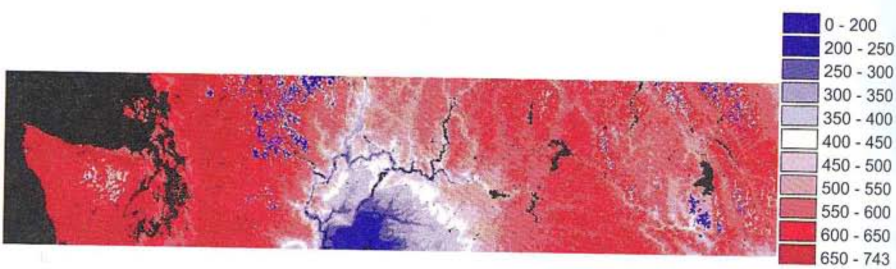

Figure 3: Map of potential Net Primary Productivity (NPP) (gC m^{-2} y^{-1}) from an integrated ecosystem model for the CLIMET transect extending from the Pacific Ocean to the Rocky Mountains in the northwestern US. NPP calculated for 1980-1997 (from Kang et al. 2002).

5. Modeling challenges in mountain areas

Modeling is a valuable adjunct to mountain research programs, sharpening our ecological understanding of phenomena at broader scales and allowing us to view multiple outcomes of our actions that would not be possible in the real world. The Mountain Research Initiative (Becker and Bugmann 2001) explicitly recognizes this value and promotes modeling as a key tool in mountain investigations and management. Numerous other modeling efforts are underway in mountain regions, as modeling becomes a more common tool in many scientific investigations. In the US, similar integrated modeling approaches at ecosystem scales have been applied to climate and landscape change in the Colorado Rocky Mountains (Baron et al. 2000). Other modeling approaches also may provide similar results as the mechanistic models. A geo-spatial model applied to Glacier Park suggests similar vegetation responses (Hall and Fagre 2003) to those described in this paper and, when applied to glacier mass balance, predicts that even the largest glaciers will be gone by 2030 under a scenario of current warming rates. The flexibility of integrated models is evident in the downscaling of RHESSys/FIREBGC components to the alpine treeline ecotone (Cairns 1994) and the upscaling to the CLIMET project. Schimel et al. (2002) describe the integrated modeling of carbon flux for all of the western US mountain areas in support of a national assessment on carbon sequestration. Thus, modeling clearly has moved beyond its development as a science tool and, increasingly, is becoming part of the policy arena.

However, a number of challenges remain. One is to develop integrated models that are interactively multi-scale. Management problems exist, and decisions often have to be made, at specific spatial and temporal scales that may not coincide with the scale of an integrated model's projections. We propose that management decisions can be greatly improved by examining other scales than those prescribed by law or policy. Encouraging multi-scale perspectives in policymaking will become increasingly important as global interactions increase with human population densities. Another challenge is to more fully integrate the drivers for human-caused landscape change and this will require better integration with socioeconomic models. While introducing even greater complexity into models that are already complex, achieving such a goal will not only improve our collective management of mountain resources but will also convincingly demonstrate the importance of mountains for people.

6. References

Band, L. E., Patterson, P., Nemani, R. R., and Running, S. W. (1993). Forest ecosystem processes at the watershed scale: Incorporating hillslope hydrology. *Agricultural and Forest Meteorology* **63**, 93-126.

Baron, J. S., Hartman, M. D., Band, L. E., and Lammers, R. B. (2000). Sensitivity of a high-elevation Rocky Mountain watershed to altered climate and CO_2. *Water Resources Research* **36**, 89-99.

Becker, A., and Bugmann, H., Eds. (2001). "Global change and mountain regions: The Mountain Research Initiative." IGBP Report 49, Stockholm.

Cairns, D. M. (1994). Development of a physiologically mechanistic model for use at the alpine treeline ecotone. *Physical Geography* **15**, 104-124.

Fagre, D. B., Comanor, P. L., White, J. D., Hauer, F. R., and Running S. W. (1997). Watershed responses to climate change at Glacier National Park. *Journal of the American Water Resources Association* **33**, 755-765.

Ferguson, S. A. (1997). A climate-change scenario for the Columbia River Basin. *In* "Interior Columbia Basin Ecosystem Management Project: Scientific Assesssment." (T. M. Quigley, Ed.), 9p. Research Paper PNW-RP-499. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Finney, M. A., and Ryan, K. C. (1995). Use of the *Farsite* Fire Growth Model for fire prediction in US National Parks. *In* "Proceedings of The International Emergency Management and Engineering Conference (TIEMEC'95)." (J. D. Sullivan, J. L. Wybo, and L. Buisson, Eds.), pp. 183-189.

Gedalof, Z., Mantua, N. J., and Peterson, D. L. (2002). A multi-century perspective of variability in the Pacific Decadal Oscillation: New insights from tree rings and coral. *Geophysical Research Letters* **29**, 2204 (doi:10.1029/2002GL015824).

Hall, M. P., and Fagre, D. B. (2003). Modeled climate-induced glacier change in Glacier National Park, 1850-2100. *BioScience* **53**, 131-140.

Hungerford, R. D., Nemani, R. R., Running, S. W., and Coughlan, J. C. (1989). "MTCLIM: A mountain microclimate simulation model, INT-414." Intermountain Research Station, Ogden, UT.

Kang, S., Kimball, J. S., Running, S. W., Michaelis, A., and Zhao, M. (2002). Comparisons of MODIS productivity and potential productivity in the Pacific Northwest and BOREAS area. American Geophysical Union Annual Meeting, San Francisco, California, US, December 5-10, 2002.

Keane, R. E., Morgan, P., and Running, S. W. (1996). "FIRE-BGC: A mechanistic ecological process model for simulating fire succession on coniferous forest landscapes of the Northern Rocky Mountains." INT-RP-484, US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT.

Keane, R. E., Hardy, C. C., Ryan, K. C., and Finney, M. A. (1997). Simulating effects of fire on gaseous emissions and atmospheric carbon fluxes from coniferous forest landscapes. *World Resource Review* **9**, 177-205.

Keane, R. E., Morgan, P., and White, J. D. (1999). Temporal patterns of ecosystem processes on simulated landscapes in Glacier National Park, Montana, USA. *Landscape Ecology* **14**, 311-329.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**, 1069-1079.

Running, S. W., and Nemani, R. R. (1991). Regional hydrologic and carbon balance responses of forests resulting from potential climate change. *Climatic Change* **19**, 349-368.

Running, S. W., Nemani, R. R., Peterson, D. L., Band, L. E., Potts, D. F., Pierce, L. L., and Spanner, M. A. (1989). Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. *Ecology* **70**, 1090-1101.

Running, S. W., and Gower, S. T. (1991). Forest-BGC, a general model of forest ecosystem processes for regional applications: II. Dynamic carbon allocation and nitrogen budgets. *Tree Physiology* **9**, 147-160.

Schimel, D., Kittel, T., Running, S., Monson, R., Turpinseed, A., and Anderson, D. (2002). Carbon sequestration studied in western US mountains. *EOS Transactions* **83**, 445-446.

Selkowitz, D. J., Fagre, D. B., and Reardon, B. A. (2002). Interannual variations in snowpack in the crown of the continent ecosystem. *Hydrological Processes* **16**, 3651-3665.

Thornton, P. E., Running, S. W., and White, M. A. (1997). Generating surfaces of daily meteorological variables over large regions of complex terrain. *Journal of Hydrology* **190**, 214-251.

White, J. D., and Running, S. W. (1994). Testing scale dependent assumptions in regional ecosystem simulations. *Journal of Vegetation Science* **5**, 687-702.

White, J. D., Running, S. W., Thornton, P. E., Keane, R. E., Ryan, K. C., Fagre, D. B., and Key, C. H. (1998). Assessing simulated ecosystem processes for climate variability research at Glacier National Park, USA. *Ecological Applications* **8**, 805-823.

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AN OVERVIEW OF CURRENT KNOWLEDGE

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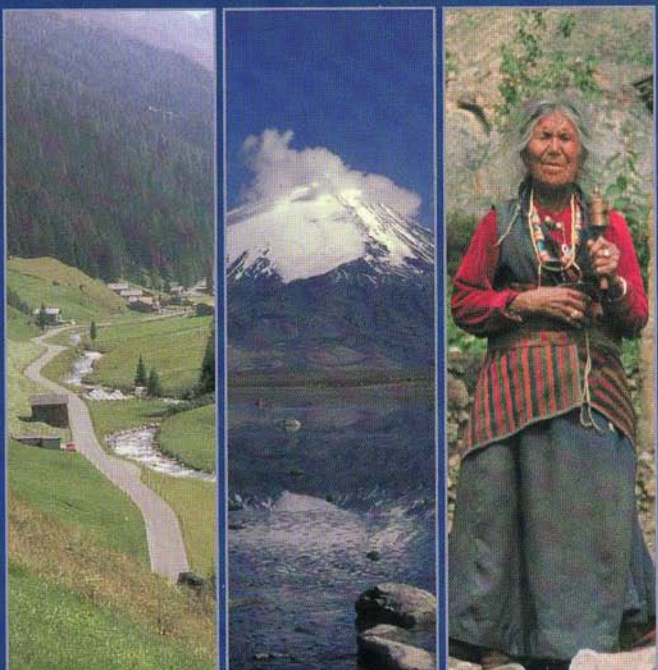

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